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A SUMMARY OF CURRENT REMOTE SENSING AND MODELING CAPABILITIES OF THE GREAT LAKES ICE CONDITIONS

by

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ABSTRACT

The capability of current remote sensing tools and mathematical models to study the Great Lakes ice conditions is reported. This report is based on a workshop held in October of 1997. In which, the feasibility of studying Great Lakes ice conditions from a combined remote sensing and modeling effort was discussed. The participants of the workshop recommended to have this report produced as a document to stimulate future coordinated field-remote sensing-modeling studies in the Great Lakes. It is believed that a well coordinated study can greatly accelerate the progress towards better forecast models.

INTRODUCTION

A workshop entitled "Assessing the Feasibility of an Integrated Modeling/Remote Sensing Approach for Predicting Great Lakes Ice Dynamics" was held on Oct. 8-9, 1997 at The Ramada Plaza Hotel Old Town, 901 N. Fairfax Street, Alexandria Virginia. This workshop was sponsored by Great Lakes Research Consortium and the U.S. National Ice Center. The purpose of this workshop was to survey current remote sensing and modeling tools to identify topics related to Great Lakes ice conditions that are highly important and thus should be pursued in the near future.

Great Lakes are ice covered at least partly in winter. The ice cover is dynamic, driven by atmospheric and lake water conditions. In turn, the ice cover modifies the mass, heat, and momentum exchange between the lakes and the atmosphere. It insulates the lakes, and reduces light penetration. Its extent directly affects the intensity of the lake effect snow, which is of great concern for both air and highway traffic surrounding the Great Lakes. Moreover, ice cover alters lake water circulation, erodes shoreline, influences lake water levels when it melts. It also has a high potential to impact water quality, fisheries and other aspects of the lake ecology.

Remote sensing has been used to survey ice conditions for many years. Both ice coverage and concentration can now be obtained daily through the Internet. As the sensor and processing techniques improve, more and better data on ice conditions are expected in the future. However, for long term (days to months) planning needs, it is desirable to predict ice cover conditions on a broad range of time scales (days to months) and interactions between the ice and the shoreline, fish population, as well as other environmental parameters.

This workshop covered three topics: remote sensing tools, modeling, and operational activities. The list of participants, speakers and a brief summary of their talks are given in the appendix. At the end of this workshop it is decided that a state-of-the-art summary should be composed for the remote sensing and modeling capabilities of Great Lakes ice conditions. This summary will serve to identify the immediate needs in advancing our ability to control ice related problems over the Great Lakes.

This summary is organized into three tables, two for remote sensing and the third for models. In these tables, the currently available tools, the parameters derivable from them, the accuracy, and constraints are listed. It is important to point out that remote sensing and modeling are two complimentary tools for understanding the ice conditions. Modeling requires high quality and detailed data for validation. Remote sending provides such data. Remote sensing requires guidance from modeling to determine the relative importance of parameters. A well coordinated effort between these two efforts can accelerate our ability to manage ice related problems in Great Lakes.

SUMMARY OF TOOLS

The remote sensing tools and mathematical models are organized in the following tables.

Table 1A. Remote sensing - Sensors.

Sensor	Advantage	Disadvantage	Class	Status	Resolution time/space/coverage
SAR	High spatiali resolution, large areal coverage, see through clouds and darkness, ice signatures have relatively large dynamic range	Data have less temporal resolution and are more expensive then passive radiometer sensors.	RADARSAT C-band frequency Horizontal polarization	Winter 96-present	~2-3 days/100m/400-500km (8-30m with smaller coverage, other modes with different resolution/coverage)
			ERS C-band frequency Vertical polarizations	Winter 92- present	35 days/30m/100km (3 days repeat for some ERS-1 data)
			ENVISAT C-band frequency Horizontal and Vertical polarizations	Planned for 99 launch	35 days/30m/100km or ~3-4days/100m/400km
			NASA JPL TOPSAR Interferometric SAR on NASA DC-8	Proposed for winter 99	12 hours/10m/10km (not routinely available, frequency of flight and coverage depend on the DC-8 availability)
AVHRR	Freely available from the NOAA Satellite Active Archive over the Internet	Daylight and cloud free conditions required, <10% time in ice-covered months. Night-time thermal imagery also of value	NOAA-6	June 1979-March 1983 July 1984-November1986	Twice Daily, 1.1 km at nadir, Global
			NOAA-8	June 1983-June 1984 July 1985-October 1985	Same
			NOAA-9	February 1985-Nov 1988	Same
			NOAA-10	Nov 1986-Sept 1991	Same
			NOAA-11	Nov 1988-Apr 1995	Same
			NOAA-12	May 1991-present	Same
			NOAA-14	April 1995-present	Same

Table 1B. Remote Sensing - Parameters monitored.

Parameter	Sensor	Constraint	Classes	Accuracy
Ice edge	SAR	The determination of ice edge depends on the identification of ice and open water. The backscatter from open water is typically high at small incidence angle, and vertical-polarization return is larger than horizontal-polarization.	ERS	Around 20^{0} incidence angle, provides relatively good ice/water discrimination, but there are misclassifications for moderate to high winds.
			RADARSAT	$20\text{-}50^{0}$ incident angles, provides good ice/water discrimination, misclassifications at high winds and small incidence angles.
			ENVISAT	Dual polarization expected to provide good ice/water discrimination in most cases, but only in high resolution/small coverage modes.
	AVHRR	Spatial resolution is fairly coarse so finer details are lost. Cloud cover can play a significant role.	All	Ice edge is normally discernible from water.
Concentration	SAR	Ice and water is identified and classified at high resolution to calculate ice concentration for a given area (~ 5 km^2). Less accuracy is expected for ice concentration in areas containing thin black ice or in areas with high winds.	All	
	AVHRR	Once again, resolution is relatively coarse.	All	Ambiguity exists between thickness and concentration information because of coarse resolution.
Ice types (new, first year, leads, ridge, rubble, brash, etc.)	SAR	Analysis of SAR data for ice features is operationally done through visual interpretation by trained analysts. Automatic algorithm development is still considered to be in its infancy for single frequency/polarization SAR data. Future multi-frequency/polarization imagery should improve this situation. Some ridge detection and density algorithms have shown promise. JPL and GLERL are developing an ice type algorithm for the Great Lakes ice mapping using RADARSAT data. The algorithm is to be applied to calibrate RADARSAT data and the ice classification results are compared to surface truth to estimate the accuracy of the classifier.		
Thickness	SAR	Not directly measurable, although can be inferred through signature and morphology by an experience interpreter.		
	SAR		NASA JPL TOPSAR	To be determined by the proposed 99 winter Great Lakes Campaign with multiple platform RADARs and surface truth.

Motion	SAR/AVHRR	Robust ice tracking algorithm has been demonstrated on SAR, AVHRR, and SSM/I imagery in arctic and marginal ice zones, including the Great Lakes.	RADARSAT/ ERS/AVHRR/ SSM/I	~1-3 times the pixel spacing of the input data (e.g. 100-300m for displacement using RADARSAT ScanSAR, 1-3km for AVHRR)
Pressure	SAR	Cannot be determined directly from radar signatures. Ice motions such as convergence and divergence and ice types, composition, and concentration may help to calculate ice pressure.	All	

Table 2. Mathematical Models.

Models	Physical processes included	Ice rheology	Numerical scheme	Input required
Canadian Ice Center	Dynamics only. Wind, current (can take given input, but set to zero at present) and ice internal stress.	Viscous-plastic, 10 ice types	Eulerian, projecting to transfer to semi-Lagrangian soon	Initial condition: surface wind and current, ice conditions. Time series: surface wind and current.
National Weather Service	Dynamics + thermodynamics. Dynamics are viscous-plastic (Hibler) rheology, driven by winds and, in principle, currents. Currents presently zero.	Viscous-Plastic	Eulerian	Initial ice cover Atmospheric winds 2m Temperature and humidity Downwelling shortwave Downwelling longwave Precipitation
Clarkson U. (has been applied to Bohai Sea in China, has not been applied to the Great Lakes)	Dynamics-thermal dynamics. Wind and current, thermodynamics, internal ice stress	Choice of 1. Free drift 2. Viscous-plastic 3. Viscous-elastic	Finite difference Eulerian for water and Lagragian discrete parcel, for ice.	Initial condition: ice concentration and thickness distributions, Time series: Wind, current, tide, air and water temp.

Common to all models, the output parameters include ice concentration and thickness distribution, velocity and stress fields. Also common to all models is the validation problem. This problem lies in the paucity of quantitative data, biases in observation, and the lack of accurate driving force data (such as current, air temperature and wind). Within the modeling itself, there is also inadequacy due to missing physics. The following table gives the available data and their archived locations.

Table 3. Existing field data.

Parameter	Source	Type of collection	Contact
Meteorology: air temp, wind, etc.	EC, NWS	Buoys, coastal Automatic Weather Station, ship observation	Ron Fordyce 905-312-0900 ron.fordyce@ec.gc.ca www.csuohio.edu/nws
Hydrology: current, waves	EC	Buoys, ship observation	same as above
Bathymatry	GLERL,Canadian Water Resource Institute	Ice Atlas	assel@glerl.noaa.gov
Ice	EC,GLERL	Buoy, shore observation, remote sensing	www.tor.ec.gc.ca/ice assel@glerl.noaa.gov www.glerl.noaa.gov

EC=Environment Canada
GLERL=Great Lakes Environmental Research Lab
NWS=National Weather Service

CONCLUSIONS

From the above tables, it is concluded that

1. Remote sensing capabilities are fast growing in both sensor improvements and algorithm developments. It is likely that by the end of the next decade, detailed ice conditions as listed by the parameters in Table 2 may be obtained on a daily basis over the Great Lakes at the resolution of 10m or finer. Therefore, operational needs at the time scale of a day or shorter will be met satisfactorily.
2. Modeling capabilities are dependent on individual researchers. Close collaboration with operational agencies will accelerate the development of these models. Unlike the remote sensing counter part, there is no national level push on the advancements of modeling work. However, accurate models are indispensable for forecasts and long term planning, including assessing the effect of climate change, impact of lake ecology, and other areas of long term interests. Modeling can also fill in the gap between remote sensing data, such as the evolution of ice conditions between two satellite overpasses, as well as parameters that cannot be detected by these sensors, such as deep water temperatures and pollution transport.
3. To ensure a healthy growth of both remote sensing and modeling capability, high quality field data are crucial. Remote sensing needs surface truth to check the accuracy of the classification algorithm. Modeling needs high quality field data for both input, in order to drive the computation, and for output, to validate the model.
4. High quality field data depend on three factors: timing, spatial coverage, and instruments. Lack of consideration in any one of these will greatly reduce the utility of the rest. A coordinated effort among remote sensing specialists, modelers, and field workers is required to define such field program. The data set obtained will be used for algorithm and model validation - a necessary step before these results can be trusted.

Appendix

Participants:
Tom Anderson (CCG), Raymond Assel (NOAA/GLERL), Dmitry Beletsky (NOAA/GLERL/CILER), David Benner (Nat. Ice Center), Cherly Bertoia (NIC), Daron Boyce (NWS), Tom Carrieres (CIS), Claude Dicaire (Canadian Ice Service), George DuPree (USCG), Robert Grumbine (NWS/EMC), Paul Hopkins (SUNY-Forestry), Robert LaPlante (NWS), George Leshkevich (NOAA/GLERL), Ray Lougeay (SUNY-Geneseo), Wayne Lumsden (CIS), David Martin (NIC), Gail Monds (Corps of Eng. Detroit), Selina Nauman (NIC), Son Nghiem (NASA JPL), David Norton (GLERL), Chris O'Connors (NIC), Caryn Panowicz, (NIC), David Rockwell (USEP-GLNPO), George J. Ryan (Lake Carriers' Assoc.), Hayley Shen (Clarkson University), Hung Tao Shen (Clarkson University), Guy Stogaitis (CIS), Don Taube (NIC), Paul M. Yu (Corps of Eng.-Buffalo).

Summary of talks:

1. Lougeay - Discussed AVHRR. It has very limited utility for the monitoring of extent and movement of Great Lakes Ice. Limited imagery available, especially in winter; and very limited availability of cloud-free image data. Difficult process of spatial registration associated with AVHRR data. The U.S. National Ice Center has greater access to AVHRR data than are generally available, and uses AVHRR data as a complement to other data sources.

2. Hopkins - Reviewed many possible remote sensing systems and issues related to ice mapping. The need for temporal, spatial, and spectral resolution varies with the problems. Comments on future image systems and capabilities, such at the NASA MODIS system, and other operational systems.

3. Leshkevich - Summarized the SAR capability and advantages over other sensor types for ice monitoring. The all-weather, day/night viewing capability of satellite Synthetic Aperture Radar (SAR) makes it a unique and valuable tool for Great Lakes ice identification and mapping providing that data analysis techniques and capability for using SAR data in an operational setting can be developed. ERS-1 launched in 1991 and more recently RADARSAT, an operational satellite carrying a SAR operating at 5.3 GHz (C-Band) with a horizontal polarization launched in 1995, provide an opportunity for this development. Using airborne and shipborne data as "ground truth", preliminary computer analysis of a ERS-1 and RADARSAT ScanSAR narrow images of the Great Lakes using a supervised (level slicing) classification technique indicates that different ice types in the ice cover can be identified and mapped and that wind speed and direction can have a strong influence on the backscatter from open water. During the 1997 winter season, shipborne polarimetric backscatter data, using the Jet Propulsion Laboratory (JPL) C-band scatterometer, together with surface-based ice physical characterization measurements and environmental parameters were acquired concurrently with RADARSAT and ERS-2 overpass. The scatterometer data set was processed to radar cross-section and will establish a library of signatures (look-up table) for different ice types to be used in the machine classification of calibrated satellite SAR data.

4. Nghiem - A field experiment across the Strait of Mackinac and across Lake Superior was conducted in February and March 1997. The JPL shipborne polarimetric C-band

scatterometer was mounted on board USCG ice breakers Mackinaw and Biscayne Bay to measure accurate radar signatures of various ice types in conjunction with in-situ ice parameter measurements. The experimental results show that both RADARSAT and ERS SAR can identify highly deformed thick ice relatively easily. Open water can be confused with ice for single polarization SAR systems depending on wind velocity. For dual-polarization SAR system such as ENVISAT (planned for launch in 1999), this problem can be resolved. Due to the snow cover in this region, the strong horizontal return allows RADARSAT a better signal-to-noise ratio for ice identification. Thin black ice and calm water have weak backscatter and the return signals are below RADARSAT and ERS noise floor. Thus, these types appear as "dark" areas in the SAR images and can be classified into a thin-ice category. The ability of SAR to track ice motion is discussed and an example of sea ice motion is shown. NASA JPL has also developed the airborne interferometric SAR technology that can be used for three-dimensional ice mapping over the Great Lakes, including ice thicknesss and ice type/coverage mapping. A field experiment with NASA DC-8 Aircraft flights is proposed for the 1999 winter over the Great Lakes to evaluate the use of interferometric SAR for ice thickness mapping.

5. Manore - Gave an overview of RADARSAT capabilities. Orbits every 12 hours. Complete coverage of the whole Great Lakes is done in 1.5-2 days with revisit about every 3 days. The resolution is 100 m to as fine as 25 m depending upon system settings. A 12 hour swath comparison of adjacent orbit passes is possible, thus provide better tracking and forecast than 3 day visits. RADARSAT provides data to the ice centers within hours of satellite overpass. Interpretation of water, new ice, and different ice types is difficult with incidence angle variations. Multipolarization is very desirable.

6. O'cconors - Presented products of the U.S. National Ice Service for the Great Lakes. Analysts use information from water surface craft, airborne reports and imagery, satellite imagery, etc. It is useful to look at all datasets. Today NIC is using RADARSAT extensively for wide and repeated coverage. AVHRR is still useful for ice edge detection despite its low resolution. The analysis process uses all data sources to produce final product. "Ground truth" is still very important to the image interpretation. All final maps are visually interpreted. GRASS GIS was used in the past to overlay imagery and mapped data. Now switching over to ARC/INFO. Data are made available quickly over the internet web page of the U.S. National Ice Service.

7. Carrieres - Presented the work of the Canadian Ice Service. They work in partnership with the Canadian Department of Fisheries and Oceans. The goal is to improve modeling and work closely with researchers in forecasting. The current model output includes ice thickness, trajectory, pressure state. In near future it is hoped to output a forecast in 3 to 6 hours. In the recent past it has taken about 7 days to put out a forecast. Accuracy of the forecast depends upon input data and model assumptions. The current model has 10 ice categories, no current. Some physics of thermodynamics is also missing. The current model needs better test and verification. The performance now has low correlation (r^2 =.4~.5) with observations. It also needs a "coupling" of any ocean model with the ice models. Data assimilation is very important because models need good input and ground truth data is sparse.

8. Grumbine - Discussed the thermodynamics of ice prediction models. These efforts parallel the Canadian efforts discussed by Carrieres. Check web pages at seaice@polar.wwb.noaa.gov. Also discussed issues of modeling implications even if we had a perfect model. [Standards, reliability, mission, budget, etc.] Currently experience from forecasters is essential to interpretation of model results.

9. Beletsky - Described modeling circulation in Lake Michigan. NSF/NOAA sponsored research project "EEGLE". [Check EEGLE home page.] New model based on the Princeton Ocean Model with better thermodynamics. The plan is to develop dynamic-thermodynamic ice model of Lake Michigan and collect data for model verification.

10. Hung Tao Shen - Presented state-of-the-art for river ice modeling and some examples translating it to sea ice and lake ice models. Advection and shore slip are more important for river ice environments (but should not be ignored in lake ice and sea ice models). Numerical diffusion is a big problem in most of the currently adopted models. Formation of leads cannot be accurately predicted in the presence of numerical diffusion. Current viscous-plastic rheology needs to be improved since it cannot predict ice jam. An accurate prediction of ice movement, pressure ridge/ice jam formation, and stress fields would be important products of model simulations. This will require continued effort.

11. Assel - Surveyed the archived material at GLERL on Climatology of Great Lakes Ice cover. Spatial and temporal monitoring of ice cover on the Great Lakes starts in 1960's (concurrent with the opening of the St. Lawrence seaway). Interests of Great Lakes ice conditions began due to the extension of shipping season for Great Lakes Seaway. Current (1990's) computer applications and forecasting yield half month period of ice monitoring from late December to early April. Check GLERL web site. Future plans are to provide all data from 1980-1994, plus continuous update, via the internet. GLERL uses ARC/INFO software. There will be a new ice climatology published for the Great Lakes in the near future.

12. Hayley Shen - Discussed missing physical processes in ice models. Examples of different forecast ice conditions from different rheological models are shown. There is no physics based criterion that may be used to select correct rheological models. Also, how important is wave action to lake ice formation and deformation? Currently no model has included wave effects. Some results from recent studies show that waves can cause significant ice drift. Ice can alter waves through 4 types of dissipation of wave energy: eddy viscosity, collisional, scattering, hysteresis. [Eddy viscosity and collisional are most important.] These theoretical results have not been validated by field data.

A group discussion following the presentations is summarized below:

1. In situ observation network is shrinking due to budget constraints. This puts more demand on better modeling capability.
2. Field data is sparse and not coordinated. Limited use for model verification.
3. Satellite data are expensive. Old sensors such as AVHRR are useful over the Great Lakes only when there are no clouds. New sensors such as SAR requires focused effort for algorithm development in order to extract useful parameter values, such as ice type and thickness, wind and waves.

4. Models are far from complete. Both missing physical processes and the effect of numerical methods need to be seriously considered.
5. Ridging and breakup processes are not built into operational models. Coast Guards need this information.

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